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# Dispersion tailoring of a silicon strip waveguide employing Titania-Alumina thin-film coating

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**Abstract**—We numerically demonstrate dispersion tailoring of a silicon strip waveguide employing Titania-Alumina thin-film coating using a finite-difference mode solver. The proposed structure exhibits spectrally-flattened near-zero anomalous dispersion within the telecom wavelength range. We also numerically predict the wavelength conversion efficiency for degenerate four-wave mixing, and obtain a 3 dB bandwidth of 80 nm.

## I. INTRODUCTION

In the past decade, silicon waveguides have, due to mature fabrication methods, shown a large potential in monolithically integrating all-optical communication systems on-chip [1]. Silicon waveguides have tailorable dimension, high refractive index contrast, strongly nonlinear interaction, and are naturally used in third-order nonlinear processes, e.g. degenerate four-wave mixing (FWM) that enables wavelength conversion [1]. Efficient FWM takes place when phase matching is satisfied, which requires anomalous dispersion to cancel the Kerr-induced phase-shift. Furthermore, near-zero dispersion enables broadband FWM processes, while spectrally-flattened dispersion may also be applied, for example supercontinuous generation [2].

Silicon strip waveguides, made from silicon-on-insulator(SOI) wafers, usually have the height fixed by the silicon layer thickness. Therefore dispersion tailoring, in essence, is to optimize the core width  $W$  to design the frequency-dependent propagation constant  $\beta(\omega)$ . As this optimization involves only a single degree of freedom, it remains a challenge to achieve spectrally-flattened, near-zero, and anomalous dispersion simultaneously. To mitigate this, we propose a structure using Titania-Alumina thin-film coating in-between the core and the cladding, while such a structure might also be useful for other applications that require a high degree of dispersion control [3].

## II. DISPERSION TAILORING

As shown in Fig.II inset, the proposed structure has a rectangular-shaped silicon core, with a height of  $H = 250$  nm and a variable width of  $W$ . Titania [4] and Alumina [5] thin-film layers of 50 nm are deposited on both the top and side surface of the silicon core, and then covered by a silica cladding with a thickness of around  $1 \mu\text{m}$ . The refractive index is designed to reduce in each region from the core to the cladding to prevent slot-modes [6].

Through a finite-difference mode (FDM) solver [7], we simulate  $\beta_2$  at 1550 nm versus core width in the proposed

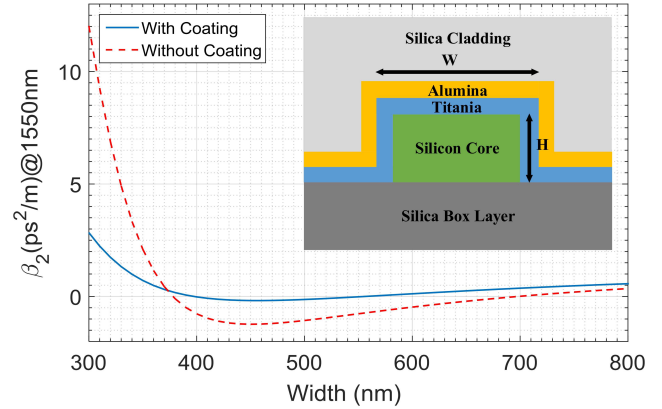


Fig. 1. Simulation of  $\beta_2$  at 1550 nm versus core width for the structures with/without thin-film coating. The inset is the cross section of the proposed structure.

structure (see Fig.II blue solid), and in a silica-cladded structure (see red dashed) for comparison. Note that we use the second-order derivative of the propagation constant with respect to frequency  $\beta_2(\omega)$  to quantify dispersion, and only focus on the fundamental transverse electric (TE) mode that has anomalous dispersion at 1550 nm. When  $W$  is in-between 400 nm and 550 nm, the structure with coating exhibits anomalous dispersion, with a maximum absolute value  $|\beta_2|$  of  $0.18 \text{ ps}^2/\text{m}$  ( $W = 450 \text{ nm}$ ). When  $W$  is in-between 380 nm and 680 nm, the structure without coating exhibits anomalous dispersion, with a maximum absolute value of  $|\beta_2| = 1.4 \text{ ps}^2/\text{m}$  ( $W = 450 \text{ nm}$ ). In this extreme case,  $|\beta_2|$  with coating reduces to one-eighth of that without coating, proving that thin-film coating can efficiently be used to tailor SOI waveguides for near-zero anomalous dispersion.

The refractive index of the coating depends on the investigated thin-film materials. It is possible to tailor dispersion by varying the thickness of each layer. We simulate  $\beta_2$  versus wavelength in the telecom range (1460 nm-1625 nm) based on a core dimension of  $250 \text{ nm} \times 450 \text{ nm}$ . As shown in Fig.II,  $\beta_2$  tends to be positive when the thickness of Titania layer  $T_t$  increases from 20 nm (blue solid), 50 nm (black solid) to 80 nm (red solid), where the thickness of Alumina layer  $T_a$  is conformally 50 nm, vice versa. Note that when  $T_t$  and  $T_a$  have the same thickness of 50 nm,  $\beta_2$  is not only near-zero in the anomalous region, but also spectrally-flattened. The

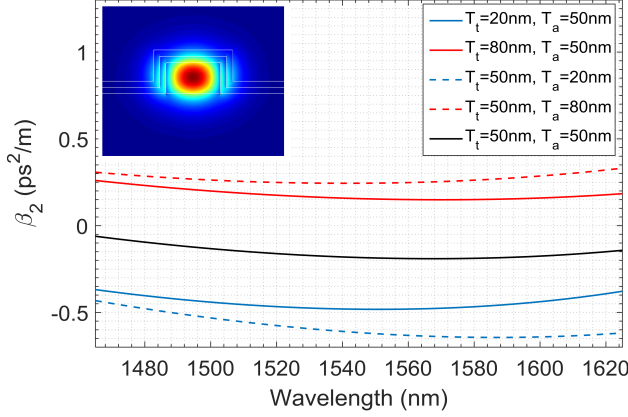


Fig. 2. Simulation of  $\beta_2$  versus wavelength at different Titania ( $T_t$ ) and Alumina ( $T_a$ ) layer thickness. The inset shows an example of the TE mode profile.

maximum  $|\beta_2|$  is  $0.19 \text{ ps}^2/\text{m}$  at  $1570 \text{ nm}$ , and  $|\beta_2|$  for other wavelengths are even smaller. As shown in Fig. II inset, a part of fields leaks into the coating. However, the mode is still well confined in the silicon core, i.e., the effective mode area in the proposed structure is  $0.75 \mu\text{m}^2$ , which is slightly larger than that of the corresponding silica-cladded structure of  $0.67 \mu\text{m}^2$ . Although the expanded mode profile leads to a reduction of nonlinear interaction, the proposed structure has a dispersion that enables efficient FWM in a large spectral range which is useful for broadband wavelength conversion.

### III. FWM WAVELENGTH CONVERSION EFFICIENCY EVOLUTION

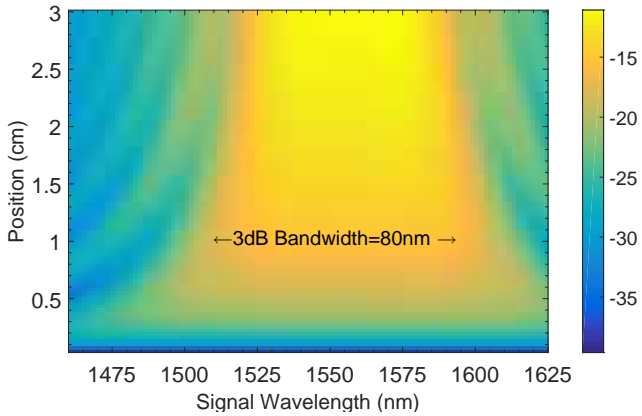


Fig. 3. Simulation of  $CE$  evolution along the longitudinal position of waveguide, pumped at  $1550 \text{ nm}$  with power of  $20 \text{ dBm}$ , while signal is tuned in telecom range with power of  $0 \text{ dBm}$ . We assume the propagation loss of  $3 \text{ dB/cm}$  and a free carrier lifetime of  $10 \text{ ns}$ . Other parameters are in Ref.[8]

Using the model and the parameters of Ref.[8], we predict the wavelength conversion efficiency  $CE$  of the proposed waveguide structure. Conversion efficiency, given by the ratio of the idler and signal power in each longitudinal position,

is often used to quantify FWM evolution, while the  $3 \text{ dB}$  bandwidth describes the spectral range with efficient wavelength conversion. As shown in Fig. III, the maximum  $CE$  increases with propagation until a position of  $1.6 \text{ cm}$ , and then saturates. The  $3 \text{ dB}$  bandwidth reduces, that is, parametric gain concentrates towards the pump in the frequency domain. For example, at a position of  $1 \text{ cm}$ , the  $3 \text{ dB}$  bandwidth is  $80 \text{ nm}$  with a maximum  $CE$  of  $-17 \text{ dB}$ . While the maximum  $CE$  is smaller than that in the corresponding silica-cladded structure ( $-15 \text{ dB}$ ), the  $3 \text{ dB}$  bandwidth increases by a factor of 2 ( $36 \text{ nm}$  for a silica-cladded structure). In addition,  $3 \text{ dB}$  bandwidth of the  $CE$  is around or even wider than  $80 \text{ nm}$  when the pump is tuned in the telecom wavelength range.

### IV. CONCLUSION

In conclusion, we propose a silicon strip waveguide structure employing Titania-Alumina thin-film coating that exhibits spectrally-flattened, near-zero, and anomalous dispersion in the telecom wavelength range. This method of dispersion tailoring is feasible and reproducible based on the SOI-compatible approaches, and can be further generalized in other on-chip platforms. The simulations also reveal that the proposed structure can be applied in broadband wavelength conversion.

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